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EXPERIMENTAL INVESTIGATION OF THE BEHAVIOR OF SOIL

UNDER A PUNCH OR FOOTING

by

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1. Introduction.

In three recent papers ^{3,4,5} dealing with theoretical problems of soil mechanics, the implications were investigated of the assumption that soil can be treated as a perfectly plastic material for which hydrostatic pressure increases the yield strength. For the case of plane strain the criterion for the slip in soil is presented in Fig. 1 in the form of Mohr's circles and their envelope where the dotted line represents a criterion proposed by Drucker and Prager (ref. 3) for the case of soils unable to take tension. One of the especially significant implication of the proposed theory is the necessity of increase in volume accompanying shearing action (Fig. 2).

It was considered advisable to check the validity of this assumption experimentally and to obtain more data for the deformation

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³D. C. Drucker and W. Prager, "Soil Mechanics and Plastic Analysis of Limit Design", Quart. Appl. Math. 10 (1952).

⁴R. T. Shield, "Mixed Boundary Value Problems in Soil Mechanics" to appear in Quart. Appl. Math.

⁵D. C. Drucker, "Limit Analysis of Two and Three Dimensional Soil Mechanics Problems", Report All-76 to Office of Naval Research under Contract N7onr-35801.

of the soil. The experiments described in this report were designed mainly to observe the two-dimensional displacement field in the soil during the indentation of a punch or footing and also to construct the pressure penetration curve relating the pressure of the punch on the soil and penetration of the punch into the soil. Those experiments deal mainly with sand although a few were performed using a garden soil and a commercial oil modelling clay called Plasteline.

2. Experimental technique.

For the experiments described in this report a special container was constructed with removable side panels made of 1/2 inch thick glass (Fig. 3). The inside dimensions of this container are: 10 inches high, 15 inches across and 6 inches back. A grid system was produced on the side surface of the soil (Fig. 5) and the deformation of the grid system was observed and traced in the glass container (Fig. 4). By taking photographs of different stages of the punch penetration (Fig. 5) and tracing from them the grid systems corresponding to each position of the punch, a displacement field could be constructed (Fig. 6) and compared with that predicted theoretically⁴ (Fig. 7). Horizontal lines in the center of the picture in Fig. 6, represent the respective positions of the punch for each stage.

It was found possible to demonstrate the movement of the individual grains of sand, and of the whole mass of the material by the superposition of photographs of two consecutive states of deformation. Fig. 8 is a composite of two such photographs of the sand taken for two positions of the punch, differing by 0.08 inch of penetration and superimposed in such a way as to match the

reference marks (A on Fig. 8) made on the glass of the container. The streaks give the streamlines of the flow.

A conventional beam type universal testing machine was used and a much greater load than was expected in the experiments was applied to the beam of the machine. A thin-walled tube with strain gages was placed between the head of the machine and the punch (2 inches across and 6 inches back, fitted to the 6 inch dimension of the container) and was rigidly attached to the head of the machine. It was found in the initial experiments that the punch, when not rigidly attached, had a strong tendency to slide to one side (Fig. 9).

The loads were measured by four resistance strain gages on the thin walled tube connected in a Wheatstone bridge arrangement. The out of balance current was measured by a sensitive galvanometer. The penetrations of the punch into the soil were measured by a dial gauge indicator.

3. Experiments.

a. Sand.

A white sandblast sand was used for the experiments of specific density $\gamma = 90 \text{ lbs/feet}^3$ and angle of repose of $\phi = 37^\circ$. The angle of repose was measured from a photograph of the cone of the sand produced on a glass plate from a funnel fixed above the plate. This sand was packed in the container by tamping with a steel rod, resulting in the increase of specific density to $\gamma = 103 \text{ lbs. per cu. ft.}$ This increase of density was consistent for all the experiments with the sand. After the packing the top surface of the sand was supported by a wooden block, then

the container was laid on its side, and the front glass panel removed to make the grid system on the sand. Horizontal and vertical grooves were made in the sand, one inch apart and approx. 0.005 inches deep. The grooves were filled with aniline dyed sand. Finally the front panel was replaced and the container was ready for the test.

The important point in the analysis of the pressure-penetration curve is that the penetration was essentially fixed by the movement of the head of the machine and the resulting load was measured but not controlled. A form of creep appears in the drop of load while the displacement is held constant. Two characteristic types of pressure penetration curves are shown in Fig. 10. They differ in the numerical values but have the same general character. Up to the top value of pressure the relation between pressure and penetration of punch is linear. It should be noticed, at this point, that there is no analogy to the linear part of the stress-strain curves for metals as sand does not exhibit appreciable elastic recovery properties on this scale.

Up to the top value of pressure the displacement field is somewhat like the flow of a fluid (Fig. 11) starting from the punch and ending on the top free surface of the sand. A part of the motion is also directed downward into the container. There is no discontinuity layer between the sand which moves and the sand at rest. When the top value of pressure is reached, a new field of displacements starts to form. A surface of discontinuity of movement of grains appears. Below this surface no displacements of sand are apparent (Fig. 8). During the formation of this new displacement field, the pressure decreases with the increasing indentation of the punch but not in a smooth manner until a

definite layer of discontinuity is formed and further displacement of the sand takes place under almost constant pressure. An example of the displacement field is presented in Fig. 6. The discontinuity layers end on the free surface at a rise of the surface level to form distinct steps (Fig. 4) and (Fig. 12).

The change of the volume of sand was measured after the experiments. An increase of volume was observed in all experiments with the sand. The ratio of the increase of the volume outside the punch to the sand displaced by the punch was approx. 2 (length of the punch 2 inches - indentation approx. 0.4 inch). No exact measurements were made concerning the areas where the change of volume took place. Only the changes of grid areas were measured. But from these measurements and investigation of the character of deformation of grid, it is clear that the main change of the volume takes place in the discontinuity layer.

b. Garden Soil.

Garden soil used for these experiments was of rather fine structure, specific density $\gamma = 62$ lbs. per cu. ft. (after sifting), moisture content 6.5% (Measured by the change of weight after heating for 5 hrs. at 75°C) with an apparent angle of repose of 44° . (Measured in the same way as for the sand.) The same technique was used as for the sand. With the same method of packing, the resulting specific density varied from 80 lbs. per cu. ft. up to 120 lbs. per cu. ft.

The pressure-penetration curve (Fig. 13) was gradually increasing up to the moment when the experiments were stopped at which stage there was interference due to the sides of the container.

After some indentation by the punch, a separation of the

soil in the form of cracks appears at a distance from the bottom corners of the punch. They are inclined at approx. 45° downwards (Fig. 14). After some further indentation, the second set of cracks appears below the first ones. At that phase of deformation, the main displacement takes place in the column of soil under the punch (Fig. 15) forming two distinct vertical layers of discontinuity. Between these layers and cracks there is small movement of the soil. In the area above the cracks there is practically no displacement of the soil. In the experiments with the garden soil, there is no appreciable change of the upper free surface, and the penetration is accommodated by an increase in density in the region below the cracks. Fig. 16 gives us the displacement field for the experiment with the soil.

The pressure-penetration curve shows a few changes of the slope corresponding approximately to the point of formation of cracks in the soil. Quite appreciable creep appears nearly from the beginning of the experiment (curve "b", Fig. 13) and other noticeable visco-elastic properties are exhibited by the soil.

c. Modelling Clay.

Commercial oil modified modelling clay, Plastiline, of specific density $\gamma = 90$ lbs. per cu. ft. was used for the experiment. During packing into the container special care was taken to prevent the formation of horizontal layers. The glass panels were covered by a thin layer of viscous mineral oil to prevent sticking of the Plastiline to the glass.

The pressure-penetration curve is presented in Fig. 17. It was not continued because of interference by the sides of the container. Quite appreciable elastic deformation was exhibited by

the Plasteline. The movement of the Plasteline after a considerable indentation of the punch is shown in Fig. 18. There is no sign of formation of discontinuity layers. Displacement patterns for the Plasteline are presented in Fig. 19.

3. Discussion.

It appears from the deformation of the grid system (Fig. 6) that some packing still takes place in the sand up to the maximum value of the pressure (see changes of the lower grid's levels) although there is already present the movement of the sand in the directions which will produce the discontinuity layers in the next stage of deformation. At the point of maximum pressure, an analogy could possibly be made to the upper yield point in the mild steel, and to the formation of Lüder's bands. At that point, two symmetrical slip surfaces start to develop and portions of the sand above them move as a rigid body. With the formation of the slip surfaces, the force required for the further movement decreases, and a discontinuity layer is formed, then it starts to move under approximately constant load.

The displacement field in the sand (Fig. 6) is then in very good agreement with the deformation field given by Shield⁴ (Fig. 7) and obtained as an alternative solution to Prandtl's solution. The grid system and its displacement in Fig. 7 was computed for the angle of friction, $\varphi = 37^\circ$, which was obtained experimentally with the sand. The comparison of two pictures in Fig. 6 and Fig. 7 shows the same order and character in the change of thickness of the discontinuity layer, and in the ratio of the horizontal distance from the punch to the step on the upper free surface to the width of the punch (theoretical - 3,7; experimental -

2,8 for the left side and 3,5 for the right). This agreement is still more surprising in view of the fact that the theoretical computations have been made with the assumption of very small displacements while in the experiments we were dealing with quite appreciable deformations. Although the increase of volume in the experiments (Fig. 6) corresponds in a sense to the theoretical prediction (Fig. 7); one should remember that the latter was computed for a very small movement of the punch while in the experiments the penetration is quite large. Also the rapid decrease in load on the punch after the maximum load is reached does seem to imply that the sand, like mild steel, behaves in an unstable manner.

It is obvious from the obtained results that sand under the compression of a punch behaves in a completely different way than does garden soil or Plasteline. Much more must be learned about the validity of applying the mathematical theory of plasticity to soil but these preliminary results on sand are encouraging.

ACKNOWLEDGEMENT

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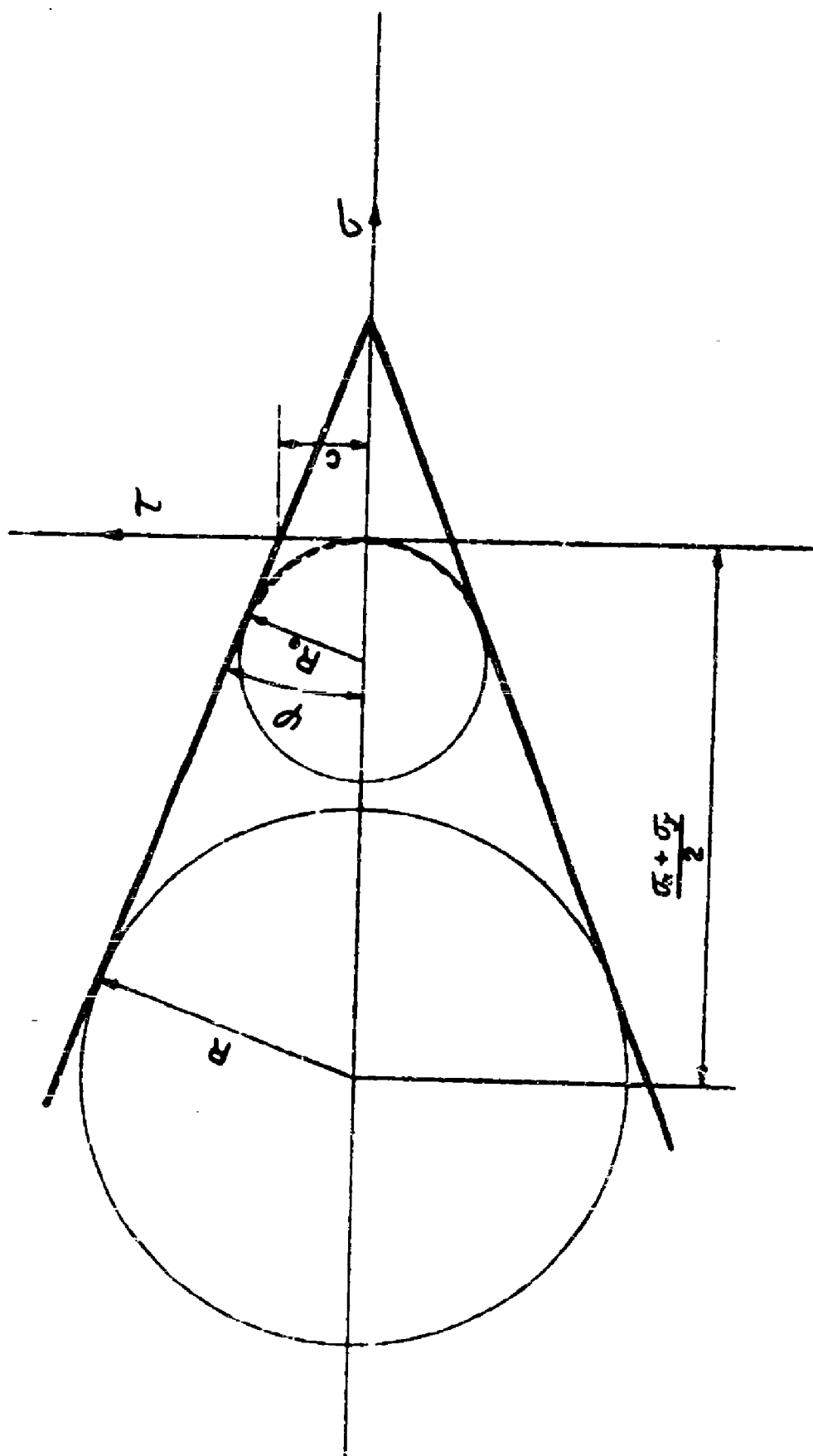


FIG. 1

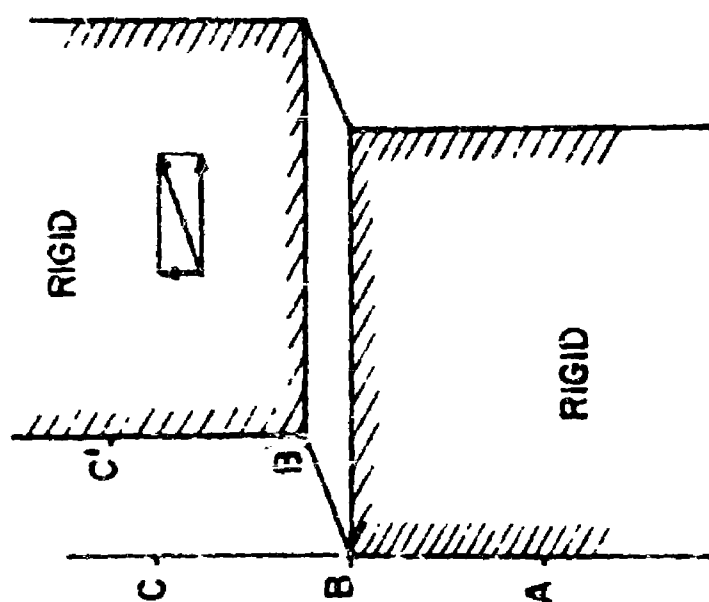


FIGURE 2



FIG 3

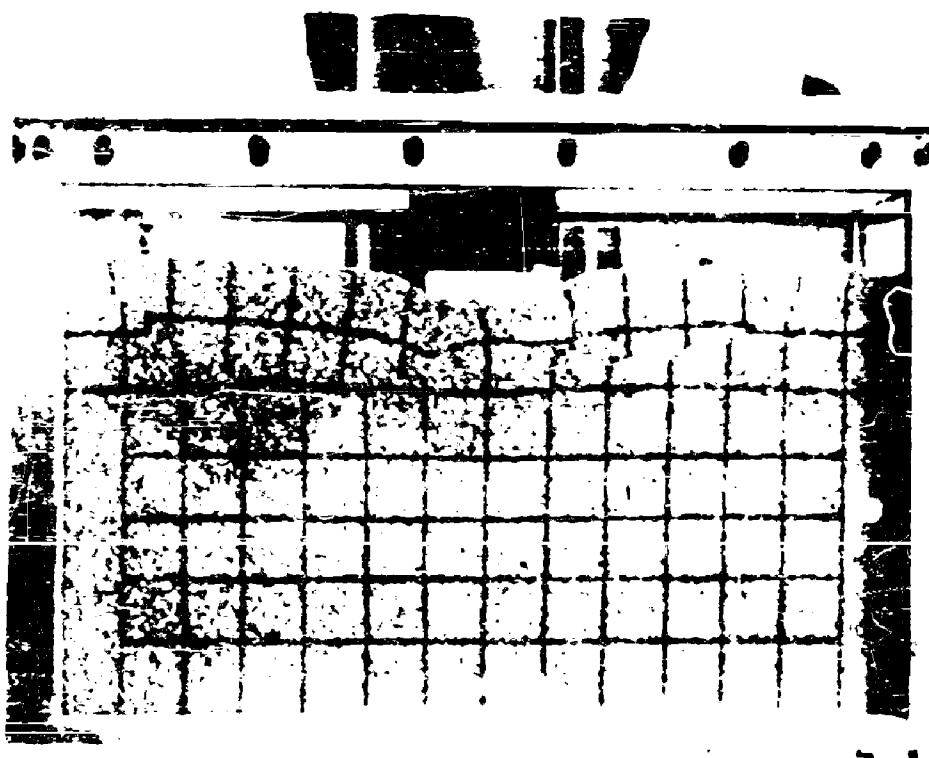
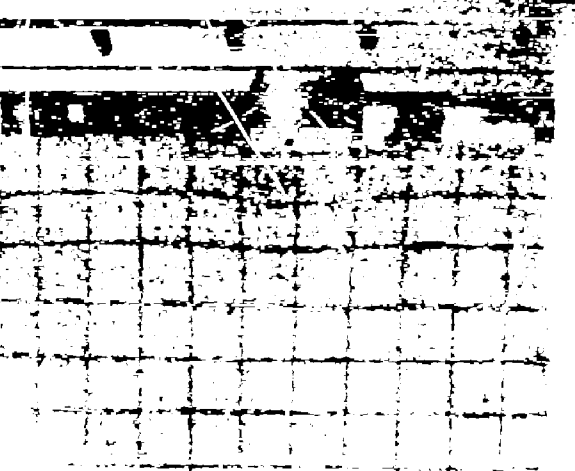
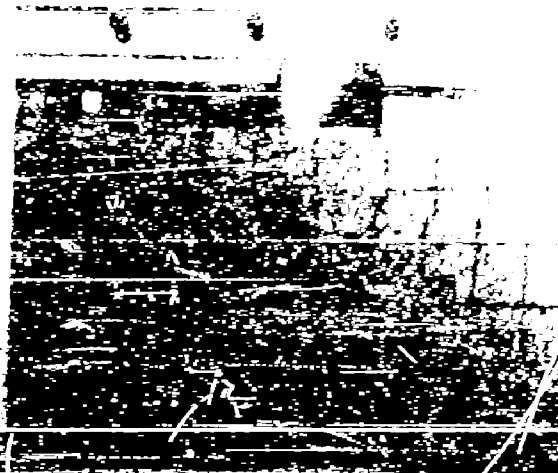


FIG 4



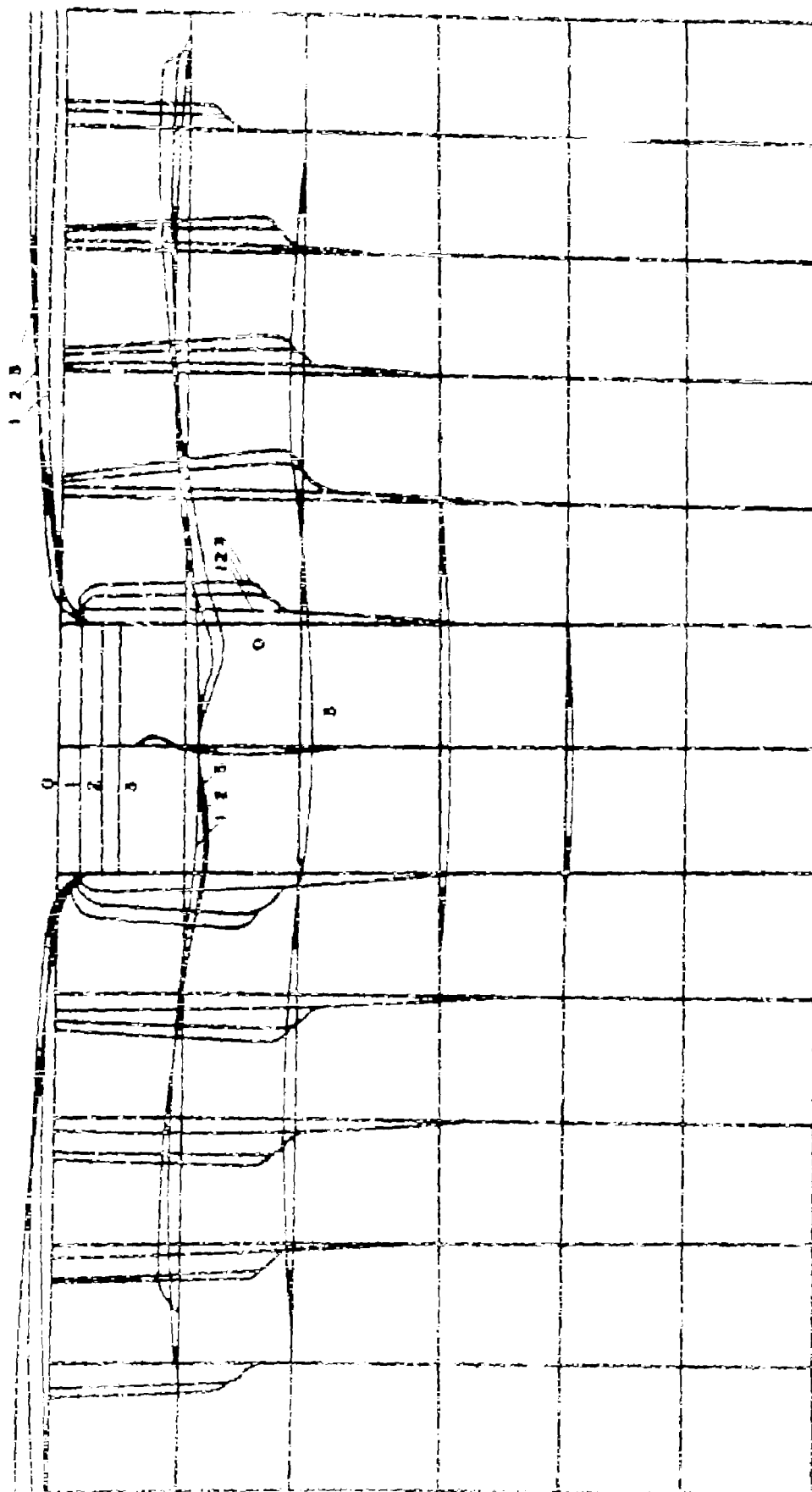


FIG. 6

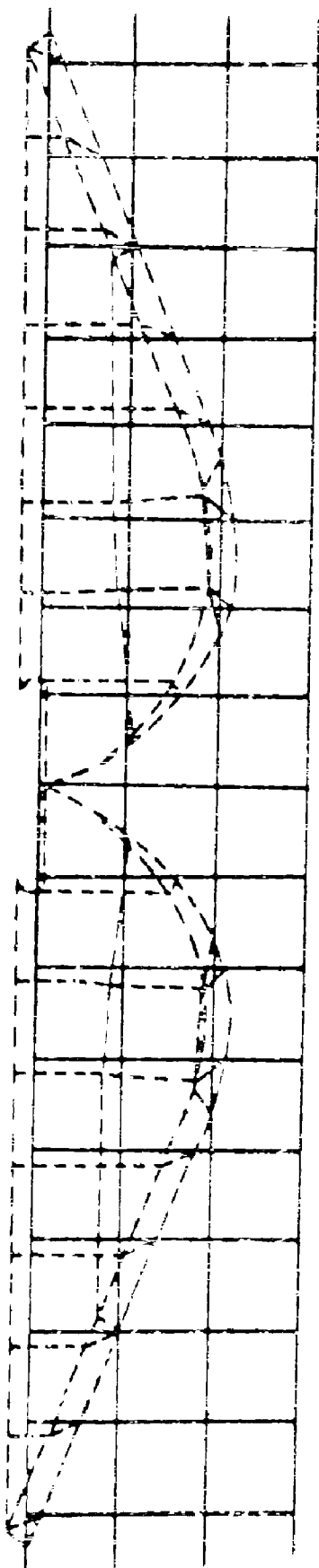


FIG. 7



FIG 8

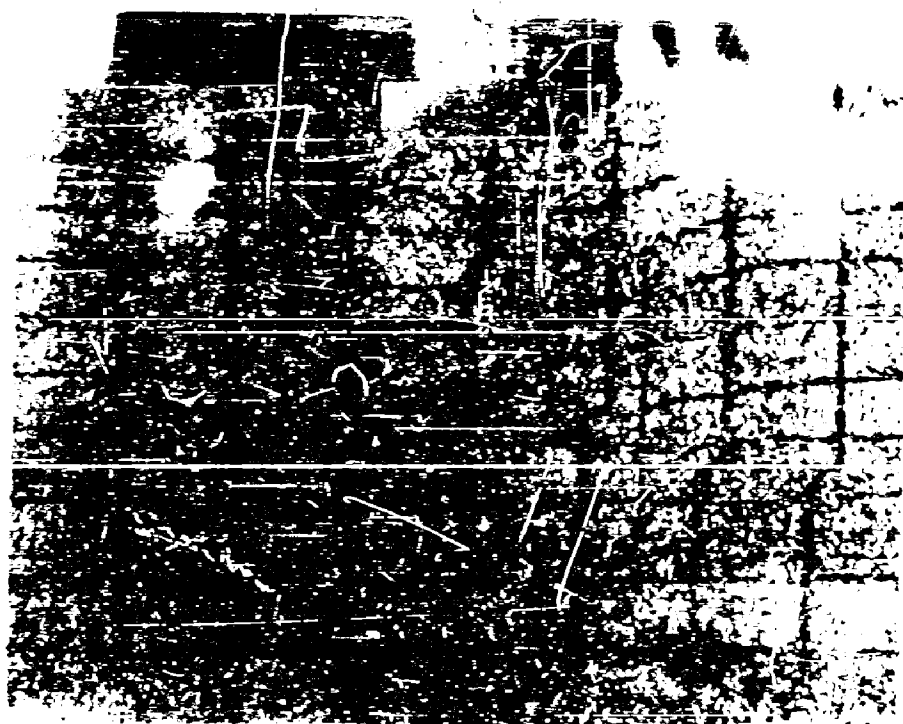


FIG 9

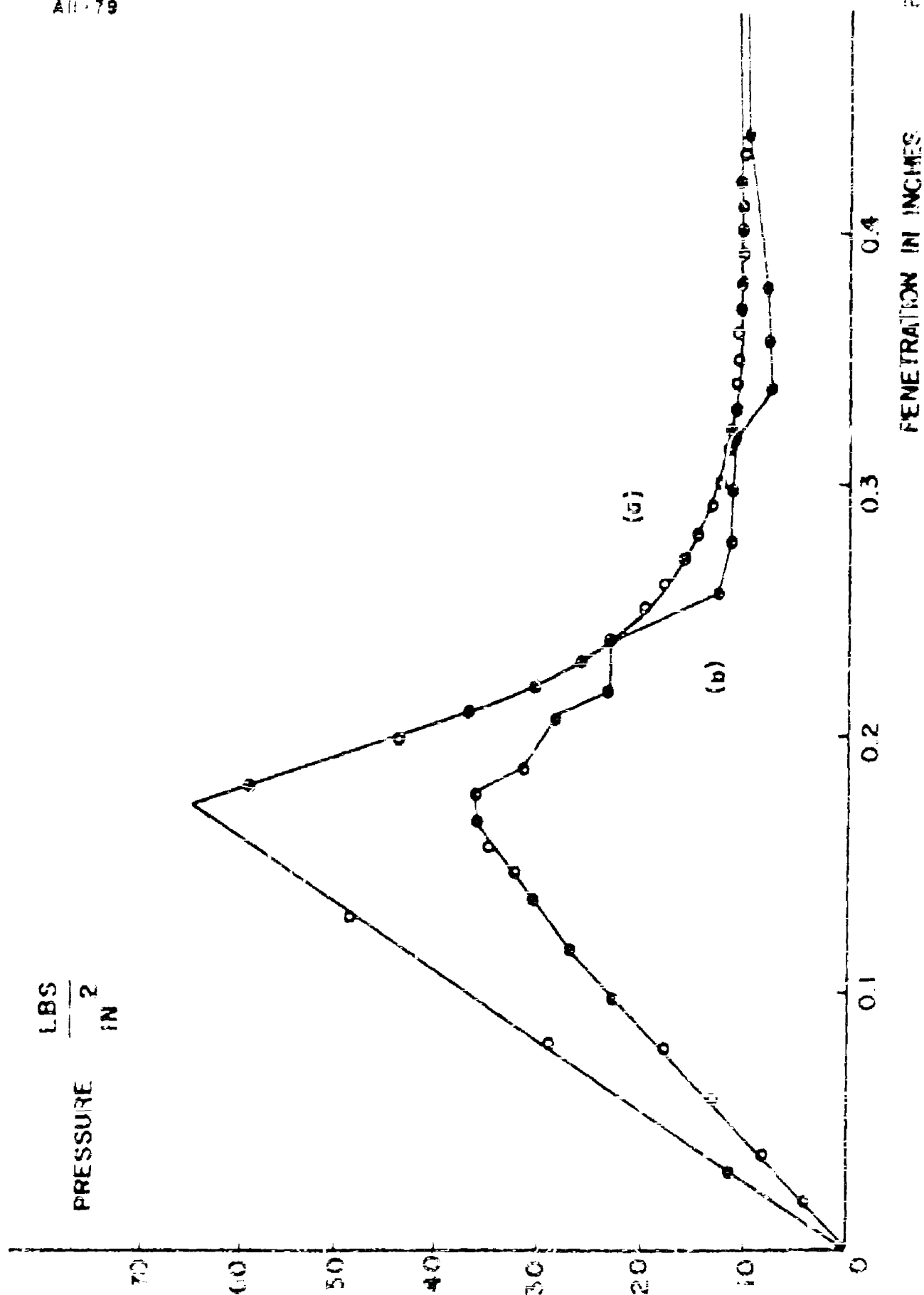


FIG. 10



FIG 11



FIG 12

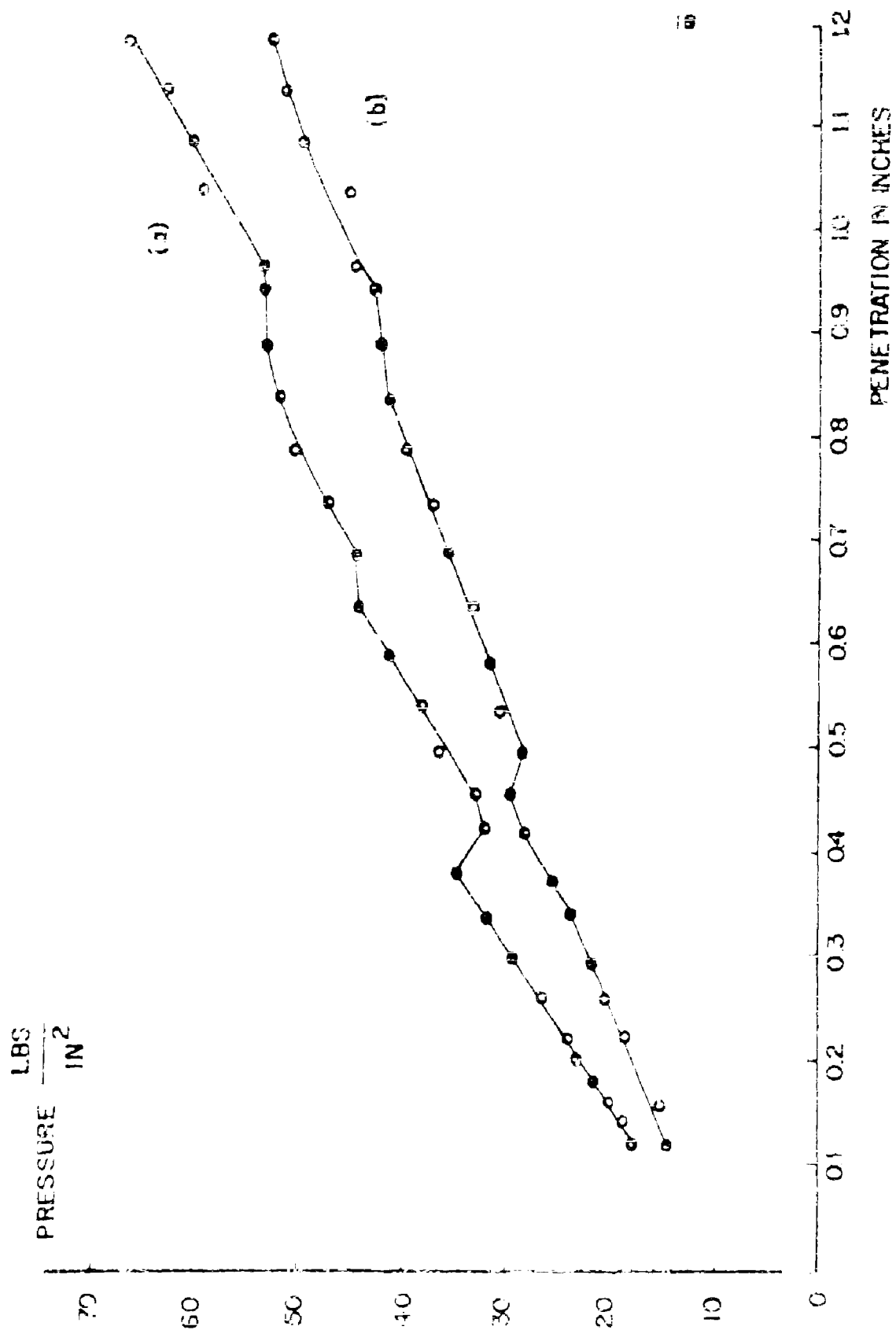


FIGURE 13

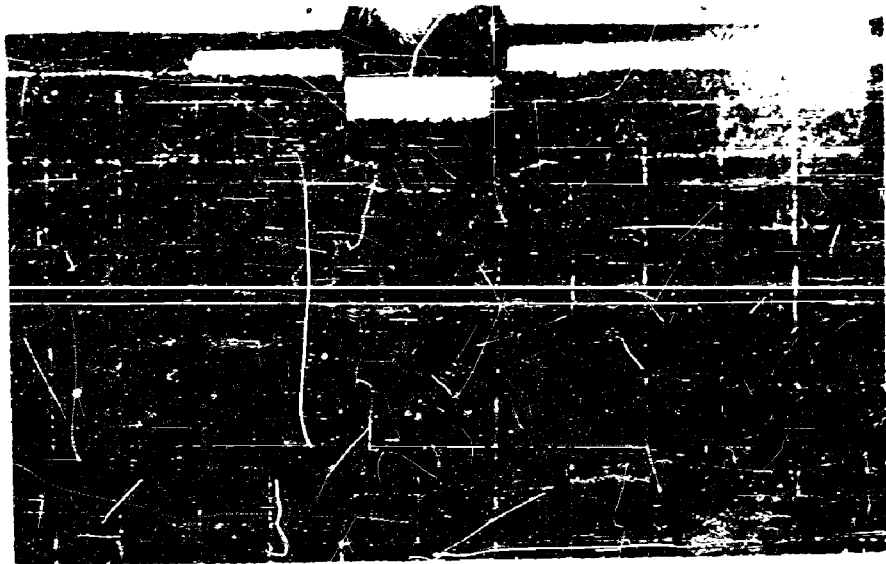


FIG 14

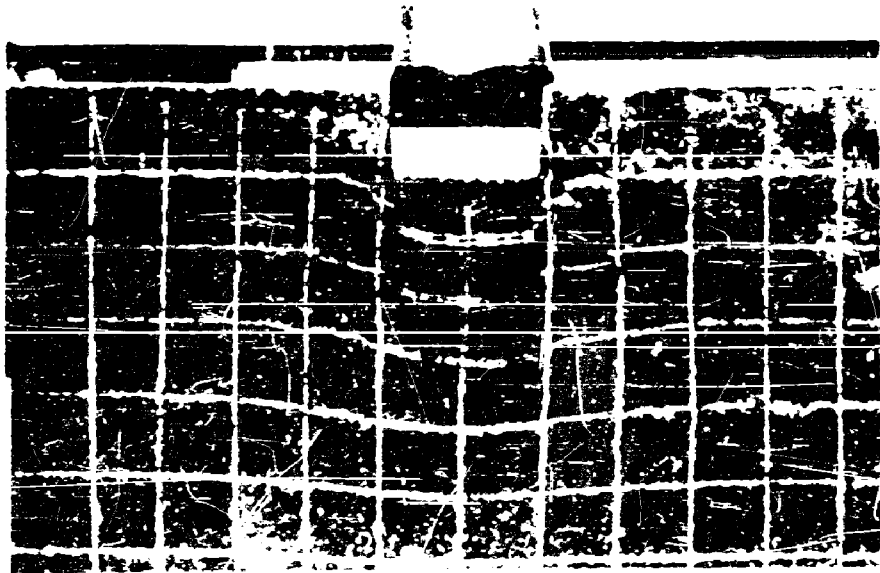


FIG 15

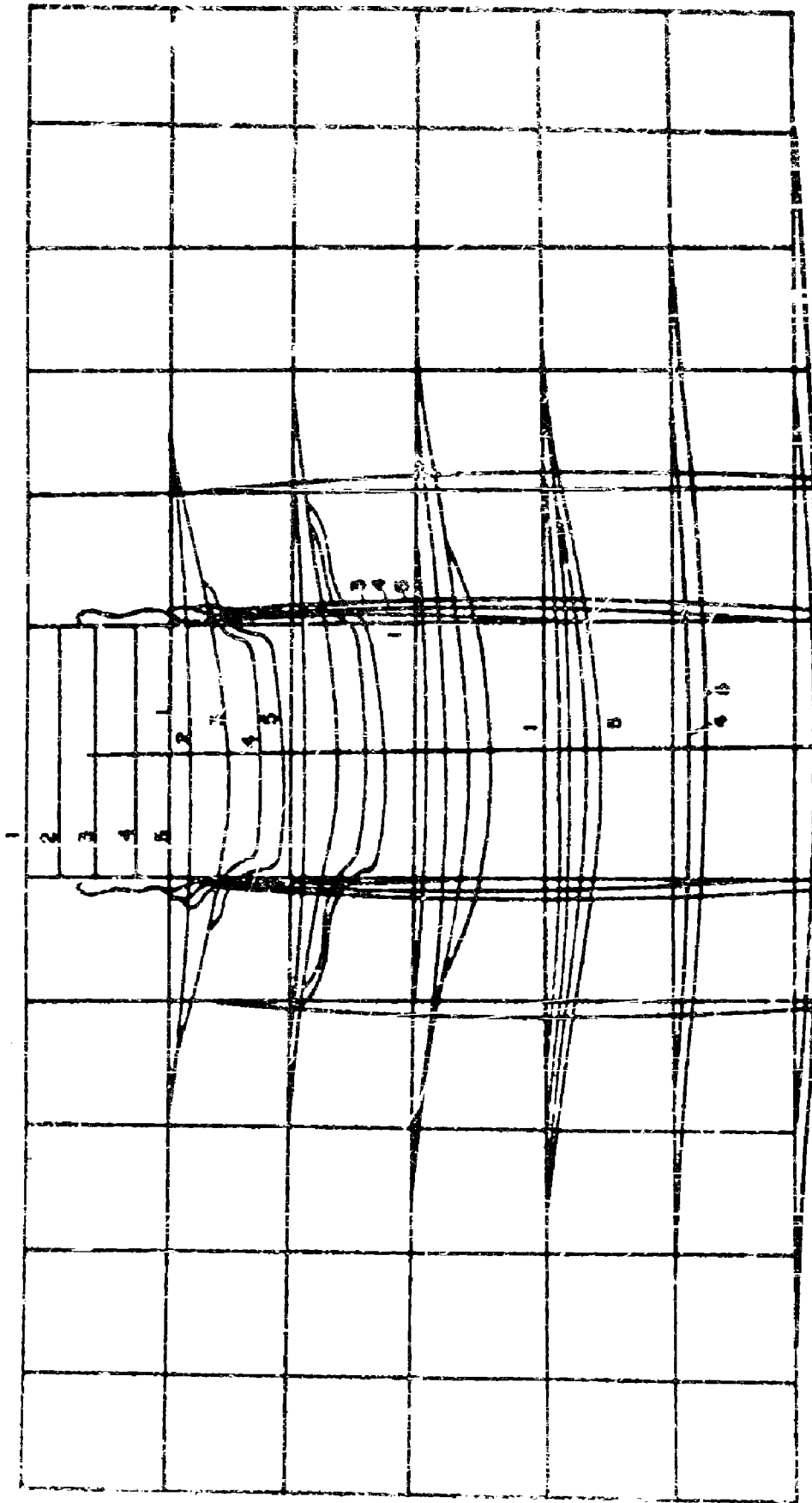


FIG 16

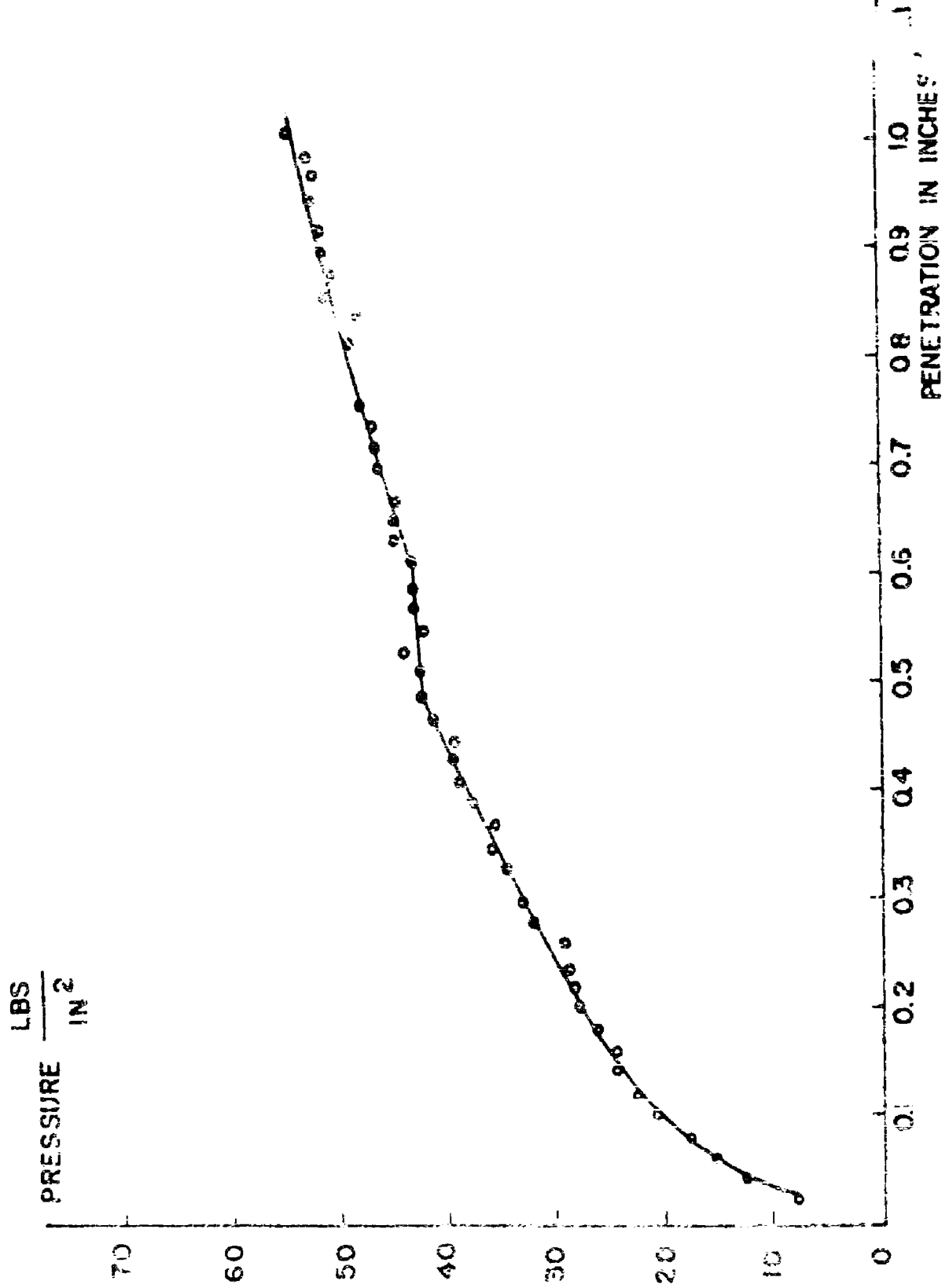
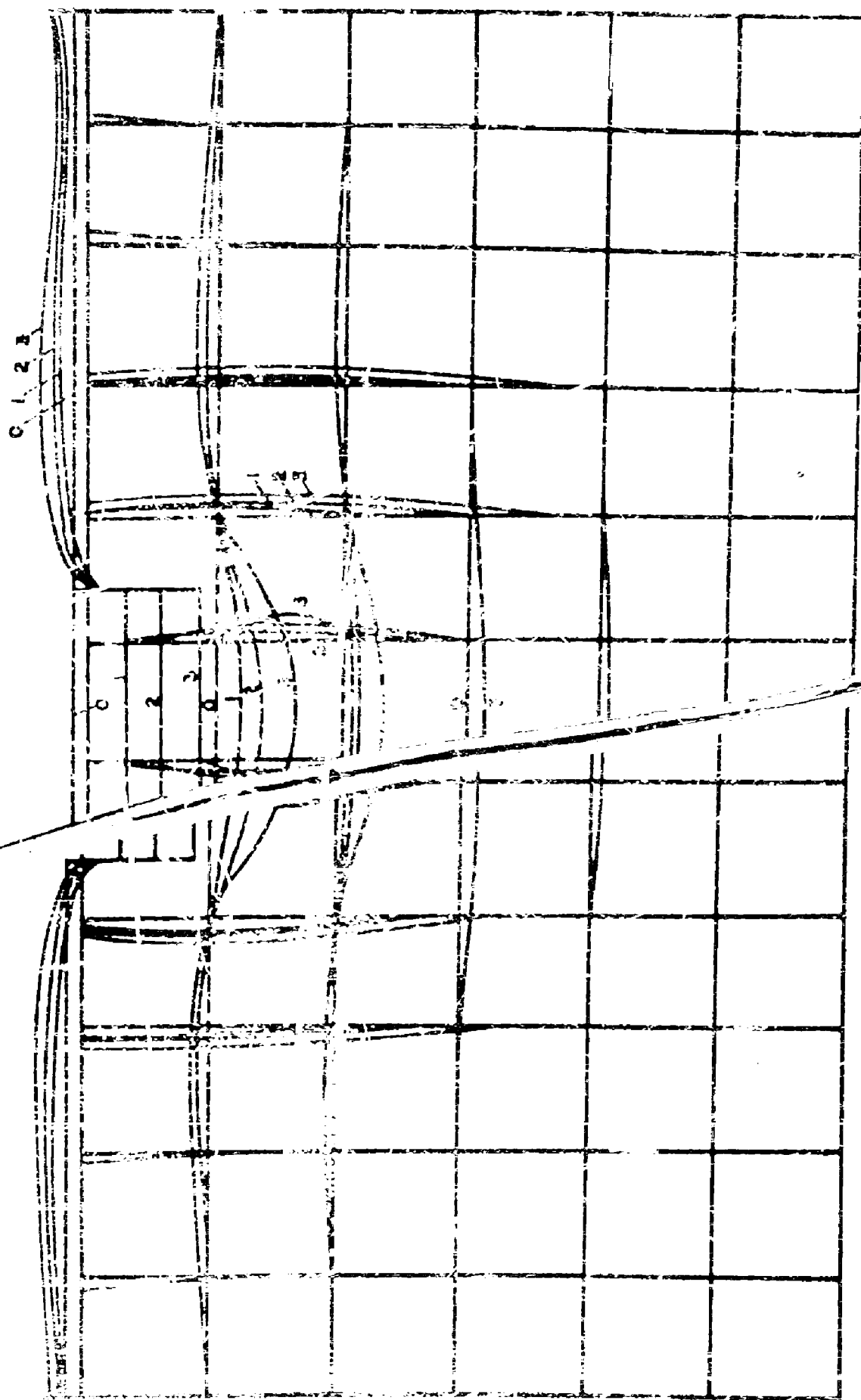


FIGURE 17



FIG 18



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